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QUANTUM PHASE SHIFT OF SPATIALLY CONFINED DE BROGLIE WAVES IN GRAVITATIONAL FIELD

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Recently, a planned experiment was described [1] to measure the phase shift of a slow neutron moving through the narrow channel. The experiment is based on the geometrical example of quantum nonlocality, shown in [2, 3]: the phase shift in the neutron wave function arises due to a change in its environment (boundary conditions) when the neutron enters a narrow channel.

The resulting phase shift can be calculated via energy arguments. The energy E of a neutron with the mass m moving in the z-direction in the spatially (x, y) restricted geometry (a tube with a square cross section with side a) is:

$$E = p_z^2/2m + (n_x^2 + n_y^2)\pi^2\hbar^2/2ma^2. \qquad (1)$$

For the case $n_x = n_y = 1$, the change of the incident momentum p_0 due to introduction of constriction is

$$\Delta p = p_0 - p = \sqrt{2mE}\left(1 - \sqrt{1 - \pi^2\hbar^2/mEa^2}\right) \approx (\pi\hbar/a)^2/p. \qquad (2)$$

The corresponding phase shift at the channel length L is

$$\Delta\varphi = L\Delta p/\hbar. \qquad (3)$$

However, the perfect crystal neutron interferometers are usually oriented horizontally. Therefore, for a neutron travelling through the channel in the horizontal z-direction, an additional shift of the energy levels takes place due to the presence of a gravitational field (in the vertical y-direction) and the reflecting horizontal, inner lower surface of the horizontally oriented channel [4].

The real potential for the neutron in the horizontal channel is

$$\begin{aligned} V(x) &= 0, \text{ for } a > x > 0, \\ V(x) &= V_0, \text{ for } x \leq 0 \text{ and } x \geq a, \qquad (4) \\ V(y) &= mgy, \text{ for } a > y > 0, \\ V(y) &= V_0 + mgy, \text{ for } y \leq 0 \text{ and } y \geq a, \qquad (5) \end{aligned}$$

where $V_0 = \frac{\hbar^2}{2m} 4\pi N b$ is the potential of the reflecting walls of the channel, N is the atomic density, b is the coherent scattering length of the wall substance, and g is acceleration of gravity.

The table shows the results of computations for the lowest energy levels E_i^g (in $10^{-13} eV$) for a neutron in the one-dimensional potential (5) ($a = 20\mu m, V_0 = 100neV$).

Level number i	1	2	3	4
Potential well without gravity	5.09	20.4	45.8	81.5
Gravity with a reflecting horizontal surface	14.0	24.5	33.05	40.6
Gravity in the potential well E_i^g	14.4	30.0	54.0	87.3

It follows from the above that (1) transforms into

$$E = p_z^2/2m + n_x^2\pi^2\hbar^2/2ma^2 + E_i^g. \qquad (6)$$

For the case where $n_x = i = 1$, for the above example, corresponding phase shift will be

$$\Delta\Phi = \left(\frac{E_1^g}{n_x^2\pi^2\hbar^2/ma^2} + 1/2\right)\Delta\varphi \approx 1.9\Delta\varphi. \qquad (7)$$

In this experiment, both the nonlocal quantum mechanical effect and the influence of gravity on the quantum phase may be demonstrated simultaneously. To separate these two effects, measurements with differently sized constriction are possible.

References

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